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14. ABSTRACT

The present work attempts to establish a unified path model for characterization as well as prediction of microstructure evolution, in terms of texture and micro-texture, in commercially pure titanium that have undergone thermo-mechanical processing. Two deformation temperatures, room temperature (cold rolling) and 260C (warm rolling), and five different deformation levels of 20%, 40%, 60%, 80% and 95% were used in the present investigation. In this report only the experimental results of texture analysis is presented. The modeling of processing path model, texture evolution and the experimental results for other temperature ranges will be presented elsewhere.

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**EFFECT OF THERMO-MECHANICAL TREATMENT ON TEXTURE AND MICROSTRUCTURE EVOLUTION OF POLYCRYSTALINE ALPHA TITANIUM**

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**Abstract**

The present work attempts to establish a unified path model for characterization as well as prediction of microstructure evolution, in terms of texture and micro-texture, in commercially pure titanium that have undergone thermo-mechanical processing. Two deformation temperatures, room temperature (cold rolling) and 260°C (warm rolling), and five different deformation levels of 20%, 40%, 60%, 80% and 95% were used in the present investigation. In this report only the experimental results of texture analysis is presented. The modeling of processing path model, texture evolution and the experimental results for other temperature ranges will be presented elsewhere.

## 1. Introduction

Commercially pure Titanium grade 2 (Timetal 50A) specimens were used in this investigation [1]. The as-received material was provided by TIMETTM in the form of plate specimens (5 pieces) in as-rolled and Mill annealed conditions (ASTM-B-265), with dimensions of 3.5" in length, 3" wide and thickness of 5/8".

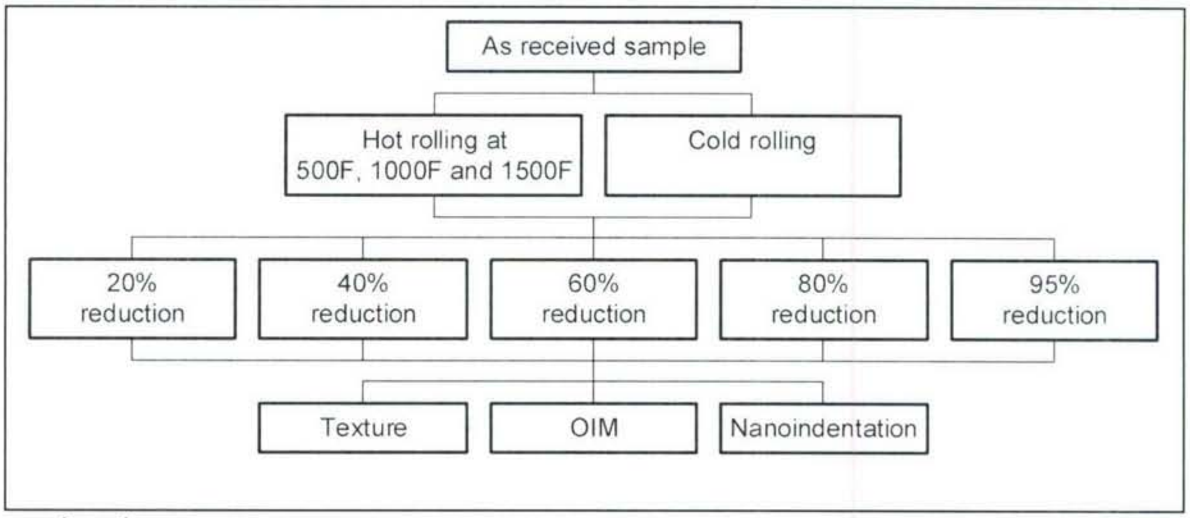
Table 1- Chemical composition (weight %)

| Material | O | C | N | Fe | H | Residual Elements | Titanium |
|---|---|---|---|---|---|---|---|
| CP Ti Gr2 | 0.25 | 0.008 | 0.03 | 0.30 | 0.015 | 0.40 | Remainder |

These specimens were cut in an Electric Discharge Machining (EDM) equipment, resulting in working samples, with dimensions 1"x3"x5/8", which were used on the thermo-mechanical processing. EDM procedures can alter properties such as fatigue through surface contamination and residual surface stresses, hence the cutting surfaces which also happen to be the future rolling planes, in this case, were ground to remove the thermally affected layer and to reduce the possibility of any induced external effect as a consequence of the necessary machining of the as-received material.

## 2. Thermo-mechanical processing

The thermo-mechanical processing of the samples for both plate and bar specimens was conducted at the rolling facility of the Materials Science Department at the Georgia Institute of Technology (Georgia Tech), Atlanta - Georgia. The equipment used was a conventional two-high rolling mill by Fenn. The schematic setup for both processing sequences is shown in Figure 1. As it can be seem, the thermo-mechanical work was chosen in such way that we have four working temperatures: 25°C (77°F), 260°C (500°F), 585°C (1000°F), 815°C (1500°F). After rolling, coupon specimens were taken for each one of the materials characterization techniques




employed.

Figure 1 – Schematic setup of thermomechanical processing .

### *3.3- Characterization Techniques*

X-ray, optical microscope, micro-indenter, nano-indenter and scanning electron microscope were used to characterize the texture and microstructure and hardness of the samples. The texture measurements were performed using a Philips X'Pert PW 3040 MRD equipped with texture goniometer. The machine settings used during the measurements (voltage and current) was 40kV and 45mA. Scan measurements from 20° to 90° (2θ angle) were run in all samples in order to determine the exact position of the peaks. Five incomplete pole figures: (0002), (10-11), (10-12), (11-20) and (10-13) were scanned in a 5° by 5° grid with Cu Kα (a = 1.54 angstroms) radiation. The rw1 data files generated by the Philips software were converted into raw archives, recognizable by PopLA [1], using PC-Texture 3.0. The software PopLA was used to recalculate the five incomplete pole figures measured and to generate the ODFs and inverse pole figures.

In order to investigate the texture gradients, measurements were carried out through-thickness at depths of 5% (19/20t), 20% (8/10t), 35% (15/20t) and at the mid-thickness (t/2) of each sample with a separate set of samples cold rolled and cold-rolled and duplex annealed.

## 4. Microstructure Evolution

The as-received sample, about 16mm thick, was hot rolled and annealed at TIMET; and characterized at the FSU/NHMFL facilities. The pole figures and ODFs for the as received sample are shown in figures 2 and 3, respectively. According to figure 2 the texture of the as received sample, nevertheless not strong, was not random showing that the <0002> directions of most of the crystals were distributed on the plane formed by the normal and the rolling directions. The orientation distribution function results shown in figure 3 confirms that the as received material is formed by a initial texture of medium intensities, 3 times random at most, with no presence of fibers or any important texture component.

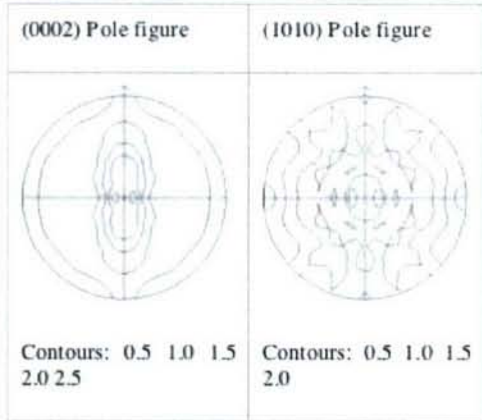



Figure 2- (0002) and (1010) pole figure for the as received sample.

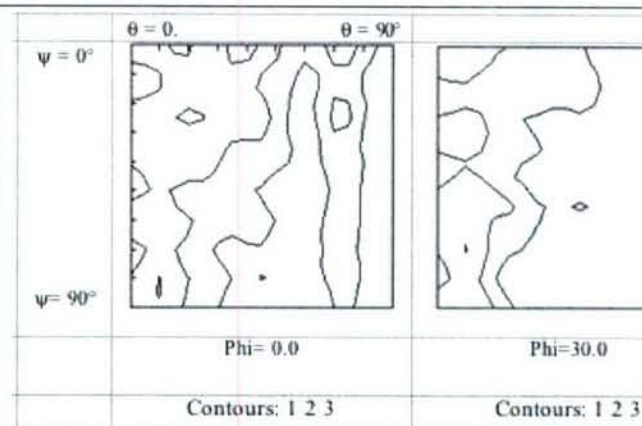



Figure 3- ODF sections of ϕ =0° and ϕ =30°, Roe notation, for the as received sample.

### 4.1 Cold Rolled Sample

Figure 4 shows the (0002) and (10$\underline{1}$0) pole figures for the cold rolled samples. In figure 4 (a), the 20% cold rolled sample, shows a low intensity, 3 times random, of (0002) poles located at the center of the figure and at four other places, two towards the rolling direction and two towards the transversal direction. As the cold reduction increases to 40%, fig. 4 (b), one can see that the two poles towards the RD remain with the same intensity as before while the poles located at the center and towards the TD have their intensities increased to 4 and 7 times random, respectively. The intensity of the (0002) pole becomes a maximum at 95% reduction when it reaches 7 times higher than a random material. The intensity of the (10$\underline{1}$0) poles does not seem to be affected by the cold rolling, increasing from 2 times random in the AR sample to 2.5 times random after 20% of deformation and to 3 times random after 40% remaining at this value until 95% of cold reduction. After 40% of deformation the distribution of the (10$\underline{1}$0) poles towards the TD vanish and from this point until 95% of cold deformation a concentration of these poles around the RD is observed.

Figure 5 shows the ODFs for the cold rolled samples and according to this figure the general aspect of the crystallographic orientation distribution changes dramatically after cold rolling. After 20% of reduction, the main texture components (around 4 times random) were the ($\underline{1}$013) [30$\underline{3}$2], the ($\underline{1}$015) [1$\underline{2}$10], and the ($\underline{3}$031) [10$\underline{1}$3], all located in the constant section of ϕ =0°. As the degree of reduction increased, the ($\underline{1}$013) [30$\underline{3}$2] component disappeared and the ($\underline{1}$015) [1$\underline{2}$10] component was intensified becoming the most intense texture component. A texture component fiber along the ($\underline{3}$031) [uvtw] component, in the section of ϕ =0°, was formed since the lowest degree of deformation and remained present with the same average intensity at all 5 degrees of deformation. A second fiber along the ($\underline{2}$115) [uvtw], in the section of ϕ =30°, started being formed after 40% of deformation no significant change in intensity was observed with increase in cold rolling reduction.

Figure-7 which shows the variation in volume fraction of the {0002} fiber texture as a function of the degree of cold rolling reduction, corroborates what was just mentioned.

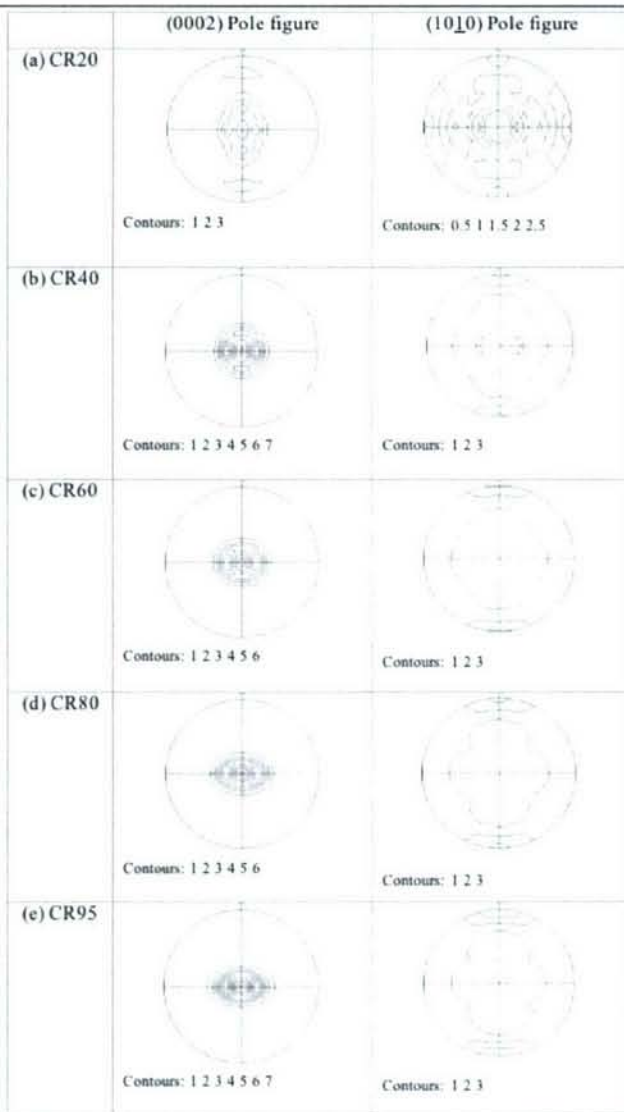



Figure 4– (0002) and (10$\underline{1}$0) pole figures of the cold rolled samples.

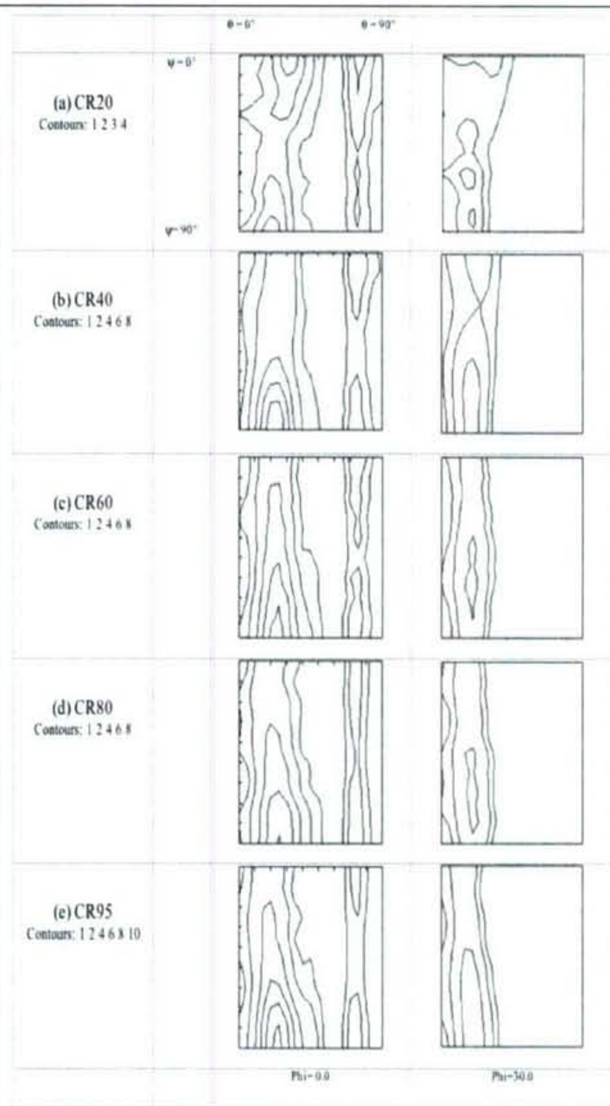



Figure 5- ODF sections of $\phi$ =0° and $\phi$ = 30°, Roe notation, for the samples cold rolled at: a) 20%, b) 40%, c) 60%, d) 80% and e) 95%.

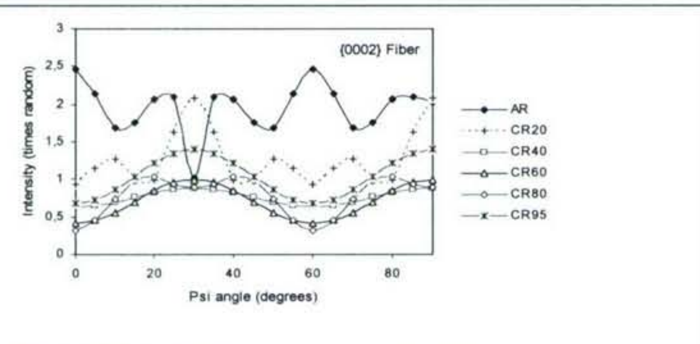



Figure 6- Development of the {0002}//ND fiber texture for the as received (AR) and 20%, 40%, 60%, 80% and 95% cold rolled (CR) samples.

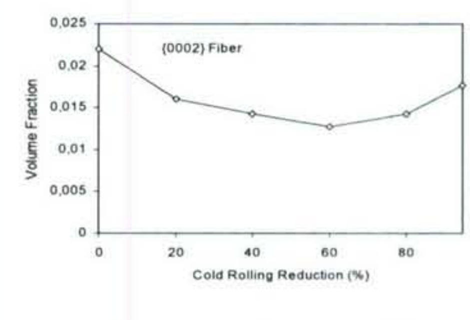



Figure 7- Variation in volume fraction of the {0002}//ND fiber texture with degree of cold rolling reduction. The as received material corresponds to the 0% cold rolling reduction.

## *4.2 Warm Rolled Samples*

The pole figures presented in figures 8 (a) to (e) show the evolution of the (0002) and $(10\underline{1}0)$ pole figures after five different rolling reductions at 260°C. At this temperature, two (0002) poles are formed towards the RD and these two poles are intensified as the degree of deformation increases varying from 4 times random after 20% deformation to 8 times random after 80% deformation. From the observation of figures 8 (a) to (d) one can see a spreading in the distribution of the (0002) poles towards the transversal direction. After 95% of deformation, the spreading increases and the 2 poles towards RD that were present in the previous pole figures no long exist.

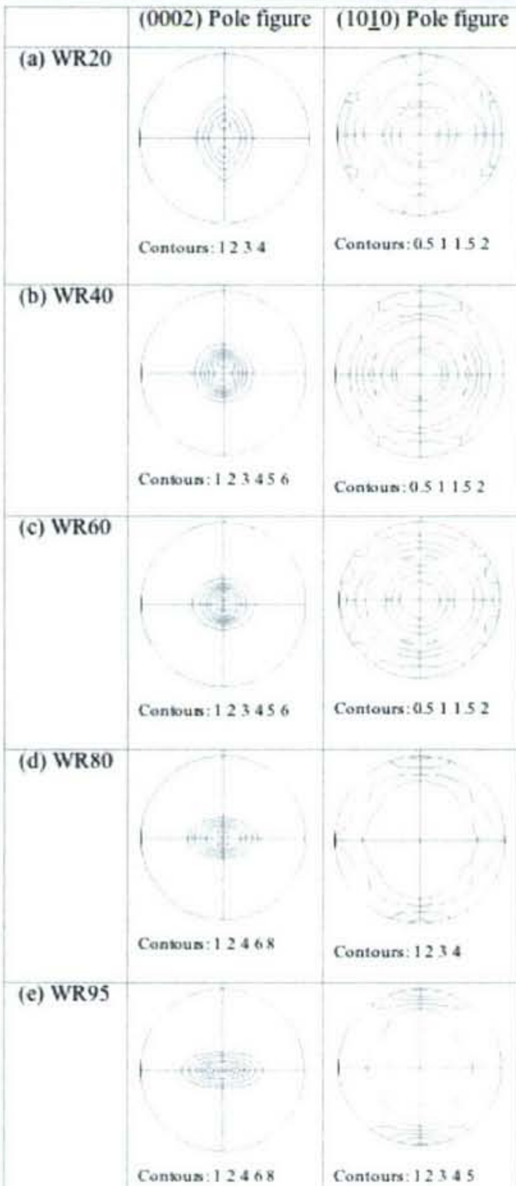



Figure 8– (0002) and (1010) pole figures of the warm rolled samples

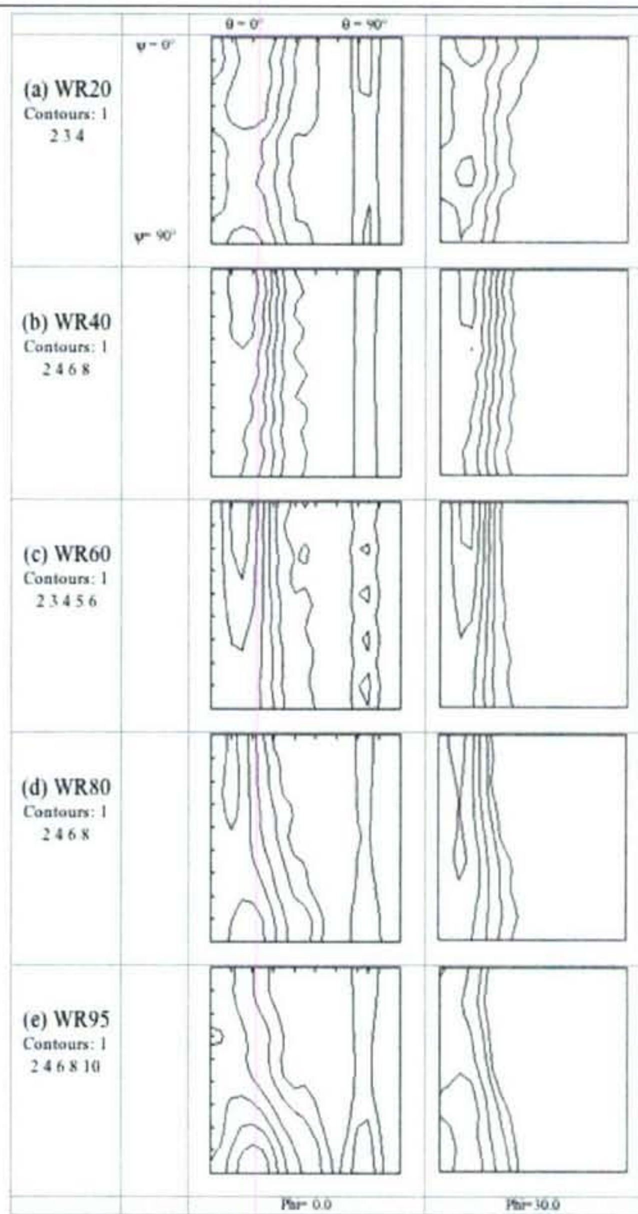



Figure 9- ODF sections of $\phi = 0°$ and $\phi = 30°$, Roe notation, for the samples warm rolled at: a) 20%, b) 40%, c) 60%, d) 80% and e) 95%.

Figure 9 shows the ODF sections of $\phi$ =0° and $\phi$ = 30°, Roe's notation, for the samples warm rolled (260°C) at: a) 20%, b) 40%, c) 60%, d) 80% and e) 95%. A formation of a fiber type of texture in the section of $\phi$ =0° at $\theta$=20°, can be observed in the WR20 sample where the maximum intensity is at the $(\underline{1}015)[50\underline{5}2]$ texture component. Figures 10 shows the development of the {0002}//ND fiber texture for the as received (AR) and 20%, 40%, 60%, 80% and 95% warm rolled (WR) samples. Figure 11 shows the corresponding variation of this fiber texture as a function of deformation.

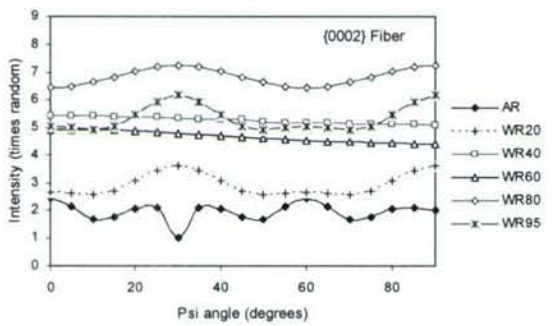



Figure 10- Development of the {0002}//ND fiber texture for the as received (AR) and 20%, 40%, 60%, 80% and 95% warm rolled (WR) samples.

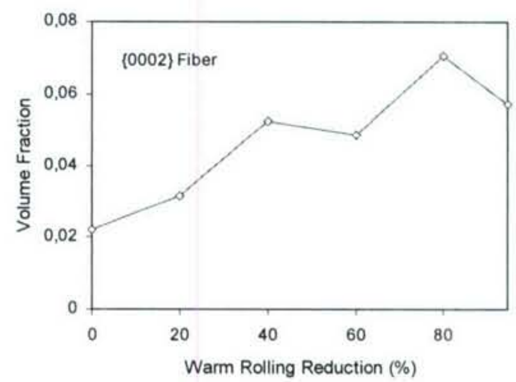



Figure 11- Variation in volume fraction of the {0002}//ND fiber texture with degree of warm rolling reduction. The as received material corresponds to the 0% cold rolling reduction.

**Summary**

A complete texture analysis of Cold Rolled and warm Rolled samples of Alpha-Titanium is presented here. For lack of space, this report only contains the texture results for room and 260C. The rest of the results for other temperatures and also the results of line broadening and micro-texture will be reported elsewhere. The numerical simulations and modeling will also be reported separately.

**Acknowledgement:**

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**Reference:**

1- G. A. Castello-Branco, Bacaltchuk, CMB, Garmestani, H, Effect of cold rolling on the annealing texture of a near-alpha titanium, MATER SCI FORUM 426-4: 701-706 2003.

### Personnel Supported

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### Journal Publications: (Published and Accepted)

1- Li, D.S., H. Garmestani, B.L. Adams, "A Processing Model for Texture Evolution in Cubic-Orthotropic Polycrystalline System", International Journal of Plasticity 21 (2005) 1591–1617

2- Saheli, H. Garmestani, A. Gokhale, Homogenization Relations for Elastic Properties of Two Phase Composites Using Two-Point Statistical Functions, International Journal of Physics and Mechanics of Solids.

3- H. Garmestani, …Processing Path Model to Describe Texture Evolution during Mechanical Processing" Materials Science Forum, Volume, 495-497, page 977-982.

4- I. C. Dragomir, D.S. Li, G. A. Castello-Branco, H. Garmestani, R. L. Snyder, G. Ribarik and T. Ungar,"Evolution of dislocation density and character in hot rolled titanium determined by X-ray diffraction" accepted for publication in Journal of Materials Characterization (2005).

5- I. C. Dragomir, G. A. Castello-Branco, G. Ribarik, H. Garmestani, T. Ungar and R. L. Snyder "Burgers Vector Populations in hot rolled titanium determined by X-ray Peak Profile Analysis" by accepted for publication in Zeitschrift fur Kristallographie (2005).

6- G. A. Castello-Branco, Bacaltchuk, CMB, Garmestani, H, Effect of cold rolling on the annealing texture of a near-alpha titanium, MATER SCI FORUM 426-4: 701-706 2003.

7- G. Saheli, H. Garmestani, B. L. Adams, Microstructure Design of a Two Phase Composite using Two-point Correlation Functions, international Journal of Computer Aided Design, Volume 11, Numbers 2-3, January 2004, Pages: 103 - 115

### Proceedings:

1. **G**. Saheli, H. Garmestani, A. Gokhale, "Effective Elastic Properties of an Al-SiC Composite Using Two-point Statistical Mechanics Approach", *The 8th International Conference on Numerical Methods in Industrial Forming Processes NUMIFORM 2004*, June 13-17, 2004, Ohio State University, US
2. D.S. Li, H. Garmestani, "Processing Path of Crystal Orientation Coefficient during Plastic Deformation", *The 8th International Conference on Numerical Methods in Industrial Forming Processes NUMIFORM 2004*, June 13-17, 2004, Ohio State University, US

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